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Uranium Mine Ventilation Costs

By Robert C. Bates

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNITED STATES DEPARTMENT OF THE INTERIOR
James G. Watt, Secretary
BUREAU OF MINES
Robert C. Horton, Director

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. administration.

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URANIUM MINE VENTILATION COSTS

by

Robert C. Bates[1]

ABSTRACT

This Bureau of Mines report converts published data on the cost of ventilating uranium mines to a common price base and analyzes these data to determine the cost per ton of uranium ore at various levels of radiation exposure control. There appears to be an exponential increase of cost as the radiation level is lowered. The 1967 base costs are extrapolated to present dollars, and some cost comparisons are given for other radiation control measures.

INTRODUCTION

Since about 1950, the Bureau of Mines has been concerned about radon-daughter concentrations in uranium mines. For a considerable time, this interest was primarily oriented toward control by ventilation. Ventilation is the most common airborne-radiation control measure used in uranium mines. However, as the mines become deeper and larger, ventilation costs increase tremendously and all available radiation control methods must be used to help reduce the radiation hazards.

In 1973, the Bureau began investigating other methods to control airborne-radiation levels and reduce ventilation requirements. Laboratory, field, and theoretical evaluations were made of sealants, bulkheading, radon removal, overpressurization, and radon-daughter removal. Costs were determined for several control techniques. For example, the cost for removing radon from the air was found to be prohibitive (2).[2]

In 1973, a Bureau study was performed of data from three reports (1, 6, 10) to estimate the cost of mine ventilation in terms that could be related to control measure costs. These were the only reports that had seriously discussed the cost of ventilating uranium mines. Since then, a study of procedures for setting standards for radon-daughters has become available (5). It evaluated the information in the three previous reports and, among other

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[1]Supervisory mining engineer, Spokane Research Center, Bureau of Mines, Spokane, Wash.

[2]Underlned numbers in parentheses refer to items in the list of references at the end of this report.

things, developed an exponential equation for ventilation costs. The information given in the literature is not directly applicable for cost comparisons. Therefore, the following text describes these three studies, describes the analysis methods, compares the results with those of Cross (5), projects the costs for various radon-daughter exposure limits, and comments on some costs of radon and radon-daughter control measures.

BACKGROUND

The three reports studied (1, 6, 10) had been sponsored by the Federal Radiation Council. The analysis base and philosophy for each were somewhat different, thus making direct comparisons difficult. For example, three different parameters were used as the exposure bases for the three reports--average working level,[3] mine index, and "last man" working level. The mine average WL might or might not be representative of the miners' exposure, because extremely low values in haulageways or intake shafts can be averaged with the supposedly higher ones in the stopes. A more representative value for the person's exposure is the mine index, which uses the weighting of occupancy time and the number of persons involved to calculate the average. The third concept, the "last man" working level exposure, represents the highest annual exposure recorded for any underground personnel. The ventilation costs are also given in two different ways, dollars per ton of ore produced and dollars per pound of U_3O_8. The information available in these reports is described briefly in the following paragraphs.

FRC Staff Report

A Federal Council (FRC) staff report (6) summarizes quite a bit of the information available on the radiation problem in uranium mines. Although various control methods were available, ventilation was the most important. Since published information on ventilation costs was not available, the FRC staff requested a number of uranium mining companies to carry out ventilation cost studies. As they state (6, p. 34), "These estimates are intended to illustrate the general magnitude of cost in a few selected mines and are not applicable to the industry as a whole." The studies were divided into two groups. One covered 11 larger underground mines that accounted for more than 20 pct of the U.S. uranium ore production, and the other group covered 3 mines that produced about 2 pct of the national total.

An exposure index was developed for the first group using time-weighted average exposures that were weighted by the number of persons involved in each of the worker categories. Estimates were made of the radon-daughter concentrations for minimal ventilation, and costs were tabulated for various levels of radiation control. Ventilation and operating costs were projected over a 10-year period. Table 1 in their report is repeated here as table 1.

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[3]"Working level" (WL) means any combination of the short-lived radon daughters in 1 liter of air that will result in the ultimate emission of 1.3×10^5 million electron volts (MeV) of alpha energy.

TABLE 1. - Ventilation cost estimates, 11-mine study, 1965 (6)

(Million dollars)

	Investment cost	Operating cost (10-year est.)	Total cost (10-years)	Estimated mine index WL
Past experience......	3.9	7.9	11.8	[1]2
Estimated ventilation cost without radon control.............	2.0	2.8	4.8	[2]10
Additional cost for radon control from 10 WL to 2 WL.......	1.9	5.1	7.0	
Estimated additional cost to reduce from 2 WL to 1 WL........	1.5	6.0	7.5	1
Total cost to control at 1 WL--10 years..			19.3	

[1]Composite mine index for 1965.
[2]Estimate of what the average WL concentration would be with normal ventilation practices.

The second group of three mines was considerably different from the 11 mines in geology, depth, extent of working, productive capacity, arrangement of passageways, numbers of openings, and so on. The reporting of the information was also different. Ventilation and operating costs were projected over a 6-year period instead of a 10-year period, and the working-level values were reported as 1-year averages, rather than the mine index value used for the 11-mine study. Table 2 of the FRC staff report (6) is given in its entirety as table 2 in this report.

TABLE 2. - Ventilation cost estimates, 3-mine study (6)

(Thousand dollars)

	Investment cost	Oper. cost (6-year est.)	Total cost (6-years)	Average concentration, WL
Past experience:				
Mine A..............	361	120	481	[1]1.4
Mine B..............	321	85	406	[1]1.5
Mine C..............	75	50	125	[1]1.5
Total...........	757	255	1,012	
Estimated for case of minimum ventilation:				
Mine A..............	63	21	84	
Mine B..............	66	18	84	[2]5-20
Mine C..............	6	4	10	
Total...........	135	43	178	

[1]Average WL concentrations in 1965.
[2]Estimate of what the average WL concentrations would be with normal ventilation practices.

RMC Report

Spencer (10) of the Resource Management Corp. (RMC) examined a number of items, including costs, associated with the control of radon daughters in uranium mines. Although literature was collected, much of the information came from personal discussions with knowledgeable government and industry people. From these discussions, Spencer decided to limit their studies to the Colorado Plateau region (Uravan mineral belt and Ambrosia Lake). Their evaluations also led RMC to the conclusion that only two approaches, historical and modeling, appeared usable for cost estimating. Historical data could provide a relationship between cost and working levels from which they could extrapolate to the average mine with a 0.3-WL concentration. Although this technique has a number of inadequacies stemming from the wide range in the characteristics of the mining operations supplying the data, it was possible for RMC to arrive at some figures in a very short time. The modeling approach, because of the complexity of the mining process itself, was too complex for the short time period of the study. Therefore, data were requested and received from eight operating mines (three small and five large) for 3 years of production, 1966, 1967, and 1968.

The three small mines had relatively small output tonnages but fairly large underground areas. Costs included supplies, labor, power, air courses, and capital investments. Capital and ventilation costs for drifts and raises were amortized over a 5-year period. The capital expenditures were reportedly amortized over a 10-year period. A summary of their data is given in table 3. The radon-daughter concentrations are given as average working levels.

TABLE 3. - Modified WL-control cost for three smaller mines (10)

Mine and year	Ore output, 10^3 tons	Average concentration, WL	Cost per ton of ore[1]	Modified cost per ton of ore[2]
Mine A:[3]				
1966..............	12	2.2	$0.33	$0.28
1967..............	9.4	2.1	1.10	.64
1968..............	7.7	.7	.51	.57
Mine B:[3]				
1966..............	[4]4.0	3.1	.47	.43
1967..............	3.0	2.1	1.38	1.08
1968..............	2.2	.6	.90	.89
Mine C:[3]				
1966..............	34.1	1.3	.21	.20
1967..............	36.2	1.3	.47	.44
1968..............	29.3	.5	2.19	1.47
Average:[5]				
1966..............	16.7	1.66	.26	.24
1967..............	16.2	1.50	.65	.52
1968..............	13.1	.55	1.79	1.26

[1]Capital expenditure written off over 10 years; some totals in RMC report (10) appeared to be wrong, so recalculated values were used.
[2]Cost of air courses amortized over 5 years.
[3]Data are for 1st half of year.
[4]1966 output of mine B was not available; assumed by extrapolation.
[5]Individual mine data averaged by tonnage ore output.

The owners of the five larger mines reported total capital assets in the original data, but Spencer used only the incremental capital expenditures for the period of interest. Therefore, certain capital costs did not contribute to the 1966-68 working level reductions. However, the improvements in concentration are shown as functions of new capital investments and increased operating and maintenance costs. The working level averages given in their tables are not based on personal exposures but are simple arithmetic averages of periodic readings taken by the mine operator in the occupied areas of the mine. In one sense, since most of the underground workers are in areas of higher radon concentration, the average exposure might be higher than the data indicate. Further analysis (based on some additional information supplied by the owners) indicated that, for the period studied, average exposures and average working levels were equal. A summary of the five-mine data is given in table 4.

TABLE 4. - Radon-daughter control costs for five large uranium mines (10)

Mine and year	Mine average WL's[1]	Ore output,[1] 10^3 tons	Total costs per ton[2]
Mine D:			
1966	2.0	132	$0.76
1967	.8	115	.86
1968[3]	.4	79	.92
Mine E:			
1966	2.2	237	.57
1967	1.1	278	.57
1968[3]	.5	154	.71
Mine F:			
1966	1.6	119	.67
1967	1.4	184	.87
1968[3]	.5	104	.84
Mine G:			
1966	2.3	212	.55
1967	1.3	276	.66
1968[3]	.7	150	.88
Mine H:			
1966	1.5	84	.64
1967	1.1	154	.51
1968[3]	.6	78	.74
Average:[4]			
1966	2.03	157	.62
1967	1.18	201	.67
1968[3]	.55	113	.81

[1]Original WL data, given for each half of each year, were weighted by ore output for each 6-month period to arrive at these yearly averages.
[2]Includes new capital costs at 10-yr writeoff.
[3]First half of 1968 only.
[4]Some values recalculated from published table (10, table 3).

The mathematical analysis, cost versus working level, of the three-mine data yielded a linear equation, and that of the five-mine data an exponential equation. Their calculations indicate that to keep the highest exposure under 0.3 WL, the mine average must be 0.15 WL. Extrapolating to this low level, they estimated a cost of approximately $1.05 per ton. Thompkins (11) took exception to this calculation and drew another curve through their data, indicating that it would be impossible to achieve less than a 0.5-WL average, regardless of how much money was spent on ventilation.

ADL Study

The study by Arthur D. Little, Inc. (ADL) for the Federal Radiation Council (1) is the most thorough evaluation of costs relative to radon-daughter control that is available. ADL personnel selected a sample of 26 underground uranium mines that would represent the underground uranium mining industry. In addition, they covered the more important producing regions, including large and small mines, old and new mines, and mines with high and low emanation rates. For early 1970, at the time of radon-daughter sampling, the 26 mines represented 29 pct of the mines, 81 pct of the production, and 88 pct of the underground employees in the United States.

The information supplied by each mine operator included working levels and costs. Some operators furnished data on percentages of underground miners receiving exposures in various working-level-month (WLM)[4] ranges. They also supplied detailed mine maps showing the location of ventilation holes, fans, secondary air bags, measured working levels, and airflow at various points in each mine. The measurements recorded were taken in March 1970. From all of the working-level data, ADL personnel were able to calculate three figures to characterize the situation at each mine:

1. Mine working-place average working level, which is the average of all working level readings reported in working places and access ways on the measurement day.

2. Maximum working level, which is the highest value reported in any working place on the evaluation date.

3. The "last man" working-level-month, which is the highest 1969 exposure recorded for an individual. The costs for ventilation and radiation control included fan power, maintenance, heating, and labor for ventilation and sampling, as well as capital costs for ventilation holes and other ventilation equipment.

After gathering the baseline information, ADL had a team of mining, ventilation, and radiation control experts study each mine to establish the changes that would be necessary to assure that a reading of 0.3 or 0.6 WL would not be exceeded in any working or travel area. These would then equate 4 or 8 "last man" WLM exposures. A design was developed for each mine to assure satisfying the 4 and 8 WLM per year standards. The incremental costs were calculated using standard unit costs. New investments such as additional drill holes, fans, bulkheads, and air heaters were included. The additional operating costs for power, labor, fuel, and supplies were also considered. Amortization for new capital items was done against 1 year's ore production from the mine. This procedure does result in higher costs than would be expected if the amortization was done more on a basis of the total ore reserves, if these had been known. Data extracted from the ADL report are given in table 5.

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[4]Inhalation of air containing a radon-daughter concentration of 1 WL for 173 hr results in an exposure of 1 WLM.

TABLE 5. - Costs and radiation levels for various degrees of control (1)

Mine	Mine working[1] place WL average, WL	1969 "last man" exposure, WLM/yr	Cost per ton of ore for ventilation and radiation control		
			Present[1]	Incremental costs	
				Present → 8 WLM[2]	8 WLM → 4 WLM[3]
1	0.48	2.20	$1.27	0	0
2	.77	11.50	.42	2.37	$2.53
3	.42	10.60	.72	.92	1.18
4	.18	1.70	.45	0	0
5	1.11	13.30	.38	.87	.94
6	.50	9.60	.57	.07	.26
7	.70	[4]12.00	1.90	.36	2.18
8	.63	9.10	1.95	4.87	11.53
9	.59	9.00	1.42	2.88	14.86
10	.58	6.50	1.23	0	4.00
11	.66	11.00	1.43	4.45	4.75
12	.40	7.70	2.62	0	3.21
13	.70	7.60	1.81	0	6.93
14	.60	[4]12.00	.42	2.22	2.60
15	.13	6.20	1.71	0	.49
16	.46	6.70	1.71	0	1.15
17	.38	9.00	1.56	.36	.91
18	.22	8.90	1.66	.18	.40
19	.33	8.60	1.99	.18	1.36
20	.15	4.00	1.60	0	0
21	.67	10.30	2.95	.27	.50
22	.27	5.60	3.80	0	.36
23	.37	13.80	3.80	.35	.60
24	.43	12.40	3.80	.33	1.84
25	.42	6.60	3.80	0	.69
26	.50	8.60	3.80	.41	1.80
Average	.487	8.635	1.876	.811	2.503
Weighted average	[5].879	NAp	[5]1.039	[6].500	[6]1.230

NAp Not applicable.
[1]From reference 1, table 39.
[2]Calculated from reference 1, tables 40 and 48.
[3]From reference 1, table 48.
[4]Approximate.
[5]Calculated, see text.
[6]From reference 1, table 42.

ANALYSIS

Since these studies spanned a 5-year period, the cost data should be put on a common base before analysis. The Consumer Price Index (CPI), also known as Cost of Living Index, was used to change all costs to 1967 dollars (1967$); hence CPI = 100 in 1967.

The Federal Radiation Council data (6) first required a calculation of the estimated tonnage for the mines over a 10-year period. In 1965, the 11 mines (table 1) produced over 20 pct of the total U.S. production,[5] which, at exactly 20 pct, amounts to 872,523 tons of ore. Therefore, the 10-year production is over 8.73 million tons. Table 6 gives the ventilation control costs converted to dollars per ton. The three small mines produced approximately 87,252 tons of uranium ore in 1965, or approximately 0.52 million tons in the 6-year analysis period (table 6). The working level month figures and 1967 dollars per ton are plotted in figure 1.

TABLE 6. - Federal Radiation Council Report 8 (6) uranium mine ventilation cost data converted to 1967 dollars per ton

Item	Total cost, millions	Cost per ton		Mine index or average WL	WLM
		In 1965$	In 1967$		
11-mine study (10-yr):					
Minimum ventilation.	$4.8	$0.55	$0.58	[1]10	120
Control to 2 WL.....	11.8	1.35	1.43	2	24
Control to 1 WL.....	19.3	2.21	2.34	1	12
3-mine study (6-yr):					
Minimum ventilation.	.18	.34	.36	[1]5-20	[2]150
Control to 1.5 WL...	1.01	1.93	2.04	[3]1.5	18

[1]Estimate of average WL with normal metal mine ventilation practice.
[2]Midrange, 12.5 WL, used to calculate WLM.
[3]Average concentration.

It is assumed that the costs supplied to Spencer (10) by the mine owners are CPI-corrected for each year during 1966-68. Table 7 summarizes the data and the conversions to 1967 dollars (1967$). These data and the production-weighted averages for all eight mines are also plotted in figure 1. As expected, because of the much greater tonnage, the weighted average is very close to the values for the five larger mines. Cross (5) pointed out that Spencer (10) neglected the succeeding years' equipment amortization and return on investment. This may have resulted in a cost understatement of 20 percent; the corrected data are also plotted in figure 1.

[5]Total U.S. production in 1965 was 4,362,614 tons (3).

TABLE 7. - Uranium mine ventilation cost data from Spencer (10), converted 1967 dollars per ton

Item	Cost per ton	Cost, 1967 dollars per ton	Average WL	WLM
Three smaller mines:				
1966......................	$0.24	$0.25	1.66	20
1967......................	.52	.52	1.50	18
1968......................	1.26	1.21	.55	6.6
Five larger mines:				
1966......................	.62	.64	2.03	24
1967......................	.67	.67	1.18	14
1968......................	.81	.78	.55	6.6

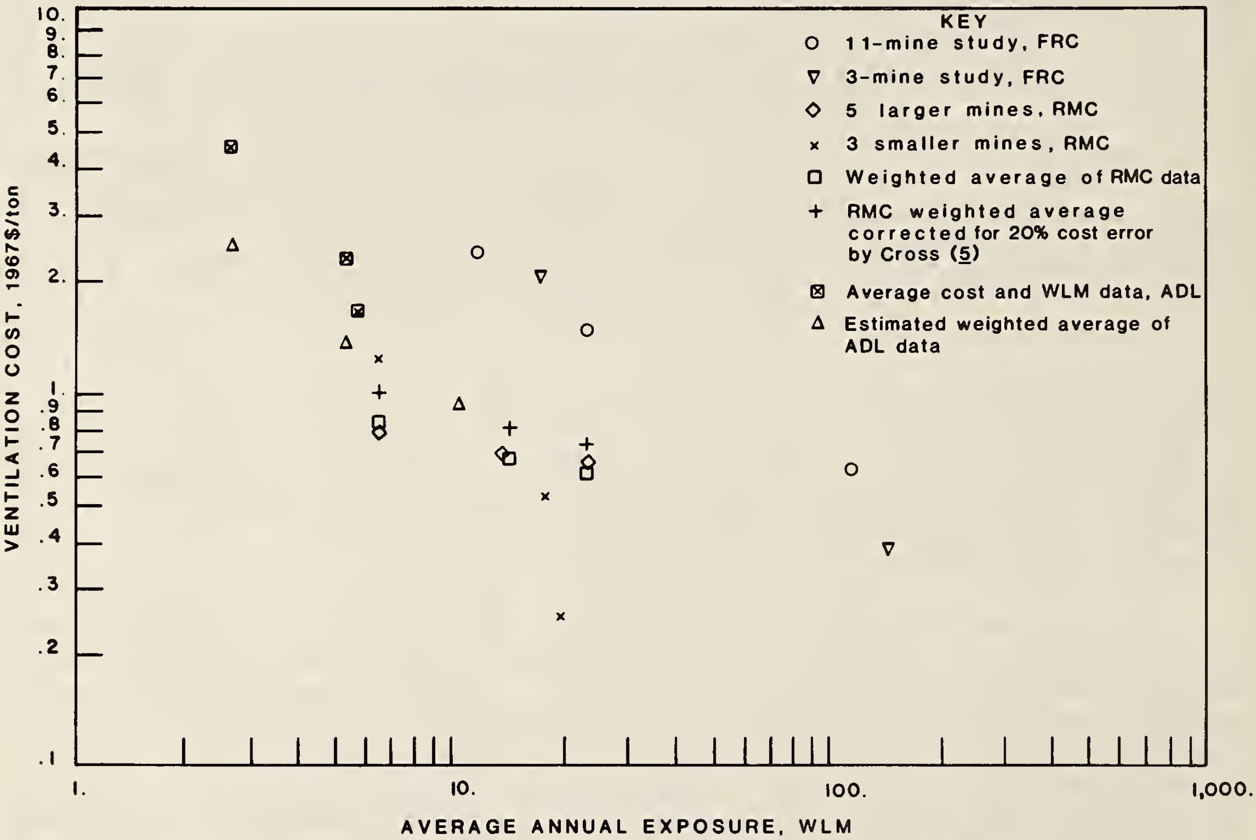

FIGURE 1. - Cost per ton for ventilating uranium mines.

The ADL study (1) had as its sole purpose to derive the total costs and impacts of decreasing the allowed radon-daughter exposure. The data for all 26 mines are given in table 5. There is considerable scatter in the information; therefore, care was taken to arrive at reasonable averages. The authors of the ADL report provided production-weighted incremental costs to arrive at 8 and 4 WLM exposures (table 5), but two key items are missing from the ADL survey--"present weighted average cost per ton" and "present average working level." These are estimated in two ways, arithmetic averages and using the observed differences in the average value and the ADL production-weighted average costs. These are given in table 8, and plotted in figure 1.

TABLE 8. - Average ventilation costs and working place radon-daughter concentrations

Item	Cost per ton, 1970$		Cost per ton, 1967$		Average WL	Average WLM
	Using table 5 averages	Using table 5 weighted averages	Using table 5 averages	Using table 5 weighted averages		
Present conditions	1.88	1.03	1.66	0.91	0.487	5.8
Last man = 8 WLM..	2.69	1.53	2.38	1.35	[1].451	5.4
Last man = 4 WLM..	5.19	2.76	4.59	2.44	[1].226	2.7

[1]Ratio calculated from table 5 averages used to calculate average WL.

The best values from the three studies are plotted together in figure 2, and a least-squares line, calculated in logarithmic space, has been drawn through the data. The equation for this line is

$$1967\$/\text{ton} = 3.134\ (\text{WLM})^{-0.3715}, \tag{1}$$

with a correlation coefficient, R = -0.75.

The 95-percent confidence limit on the expected value of the mean is, in 1967$/ton, approximately $1.10±$0.07, and for a particular value of the mean it is $1.10±$0.32. An equation was also calculated using the average values. This equation has a steeper slope and larger intercept:

$$1967\$/\text{ton} = 4.616\ (\text{WLM})^{-0.4819}, \tag{2}$$

and $R = -0.77.$

In both cases, the fit is significant at the 0.01 level (99-percentile), but the first equation is used in the remainder of this paper since it includes the corrections that are considered necessary. The exponential model developed by Cross (5) from the individual mine data is given in cents per pound U_3O_8 (1969 dollars) versus average annual exposure. By converting their equation to dollars per ton (assuming 0.22 pct U_3O_8 ore grade) and 1967 dollars, it becomes

$$1967\$/\text{ton} = 3.979\ (12\text{WL})^{-0.63}. \tag{3}$$

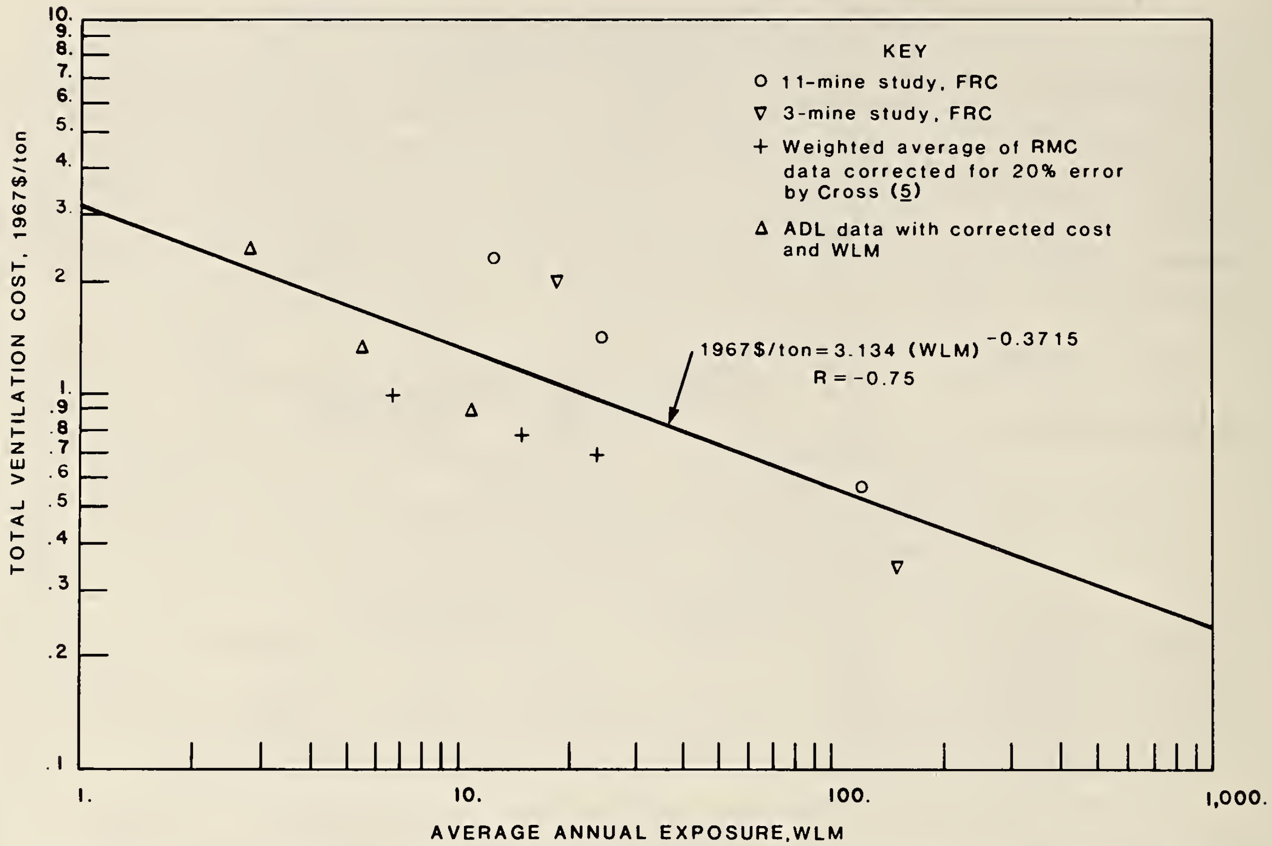

FIGURE 2. - Costs for ventilating uranium mines versus average annual exposure with regression line.

This equation has a larger intercept and a much steeper slope than the equation developed from weighted average costs and working levels. Higher cost estimates for control to 1- to 2-WLM annual exposures results when this equation is used.

APPLICATIONS

Equation 1 can be used with some limitation to estimate the industry average cost for ventilating uranium mines at any desired average working level at any consumer price index and provide comparisons with other radiation control costs.

The inflationary rise in the Consumer Price Index since 1965 is shown in table 9. Since the data used in the analysis were converted to the 1967 base CPI, it is a simple matter to multiply the calculated cost per ton by the new CPI divided by 100, as follows:

$$\$/\text{ton} = 3.134\ \frac{\text{CPI}}{100}\ (\text{WLM})^{-0.3715}, \qquad (4)$$

$$= 0.03134\ \text{CPI}(\text{WLM})^{-0.3715}.$$

An example for CPI = 250 (1980$) is given in table 10 and figure 3.

TABLE 9. - Consumer Price Index (based on 1967 = 100)

1965....	94.5	1972....	125.3	1979....	217.6
1966....	97.2	1973....	133.1	1980....	246.9
1967....	100.0	1974....	147.7	1981:	
1968....	104.2	1975....	161.2	Jan...	260.7
1969....	109.8	1976....	170.4	Feb...	263.5
1970....	116.3	1977....	181.5	Mar...	265.2
1971....	121.3	1978....	195.3	Apr...	266.8

TABLE 10. - Cost per ton at CPI = 250 (1980$) for several average WLM exposures

Average WLM	Cost per ton	
	At CPI = 100	At CPI = 250
4	$1.87	$4.68
2	2.42	6.06
1	3.13	7.84
.7	3.58	8.95

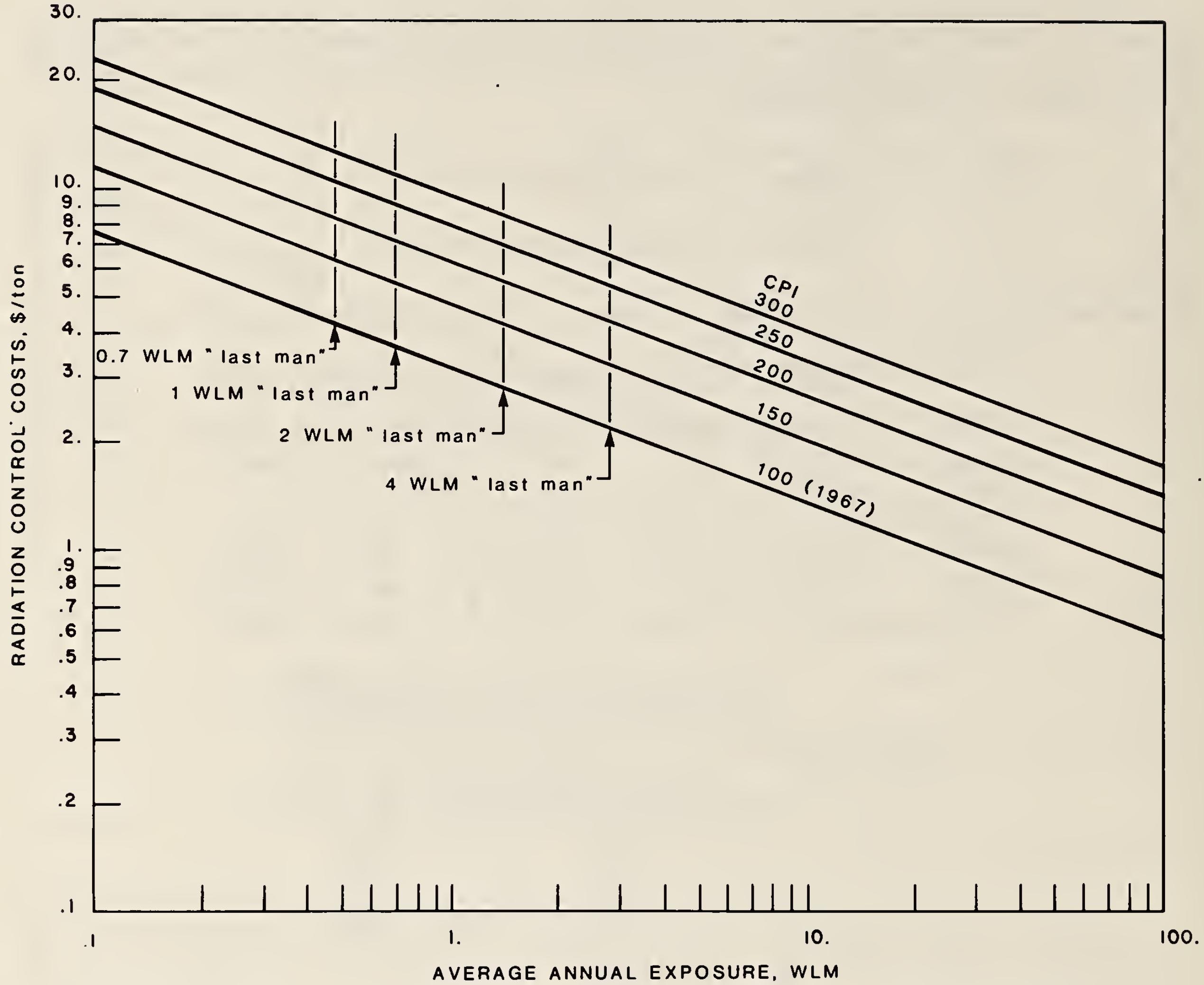

FIGURE 3. - Projected radiation control cost for different Consumer Price Indices and average annual exposure.

At this point, the "last man" exposure should be introduced. If an average working level exposure of 4 WLM is maintained, some miners will be overexposed. Therefore, we should make the projections based on limiting the maximum exposure. Information in the ADL report (1) indicated a factor of 1.478 between the average working-level-month exposure and the "last man" exposure. After incorporating both "last man" exposure and consumer price index, equation 1 becomes--

$$DPT = 0.03624\ CPI\ (LME)^{-0.3715}, \qquad (5)$$

where DPT = dollars per ton corrected for CPI,

and LME = limiting miner exposure (the highest annual exposure received by an underground employee).

Table 11 gives an example of several limiting exposures at a CPI of 250. This information, along with several other CPI's, is shown in figure 4.

TABLE 11. - Cost per ton at CPI = 250 for several limiting miner exposures WLM

Limiting miner exposure, WLM	Average WLM	Cost per ton at CPI = 250
4	2.71	$5.41
2	1.35	7.00
1	.68	9.05
.7	.47	10.34

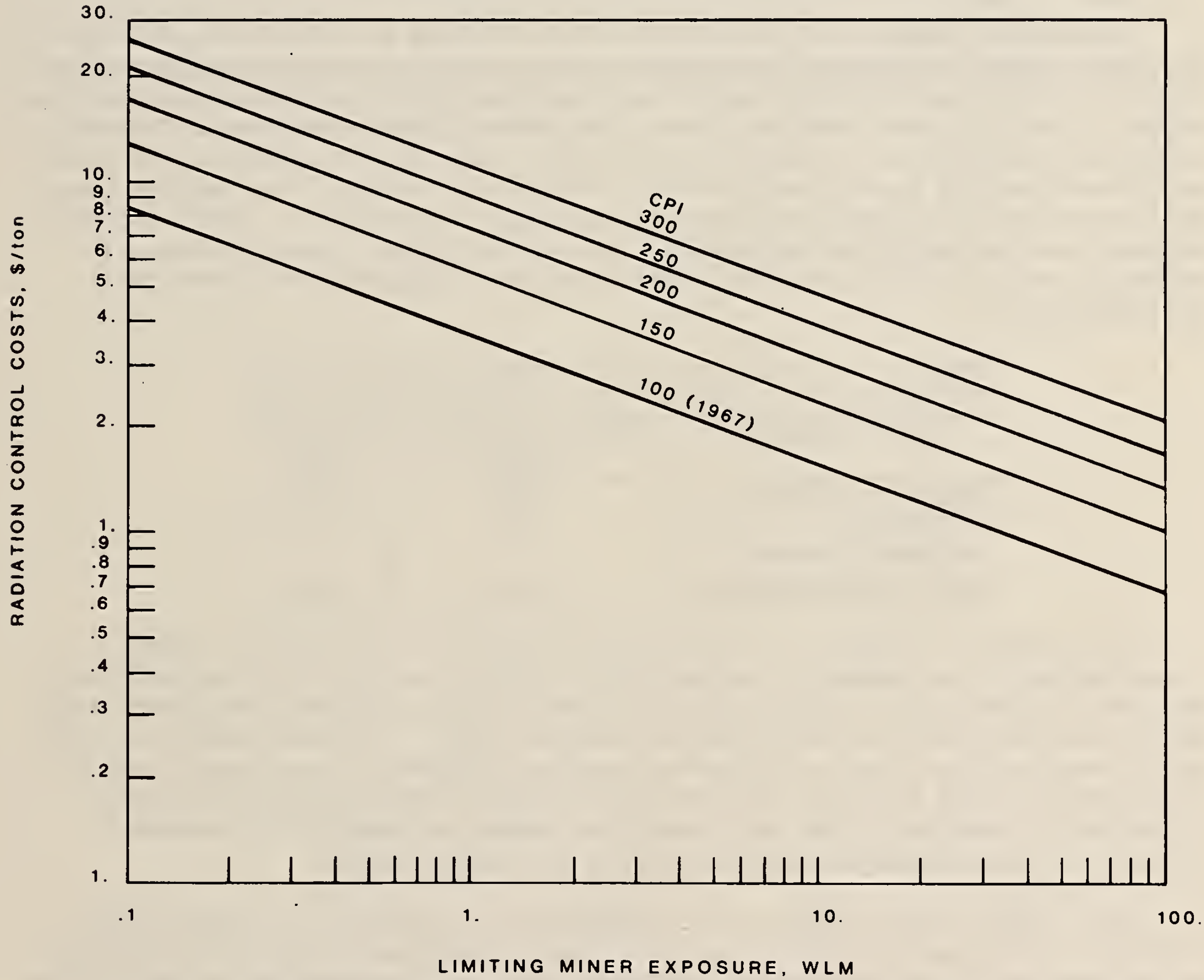

FIGURE 4. - Project radon-daughter control costs versus limiting miner exposure WLM for several Consumer Price Index values.

In looking at these projected costs for radiation control in uranium mines, it is apparent that they are significant. The underground uranium ore production in 1979 was approximately 6 million tons (8). Therefore, the estimated present cost is over $32 million per year if the industry is truly maintaining 4 WLM. If the limit is reduced to 2 WLM, the estimated total cost is $42 million; for a 1-WLM limit, it is $54 million, and for a 0.7-WLM limit, it is $62 million. Clearly, any change in permitted exposure levels can have a serious economic impact on mining costs. Also, as mines become deeper and larger than the mines in the 1965-70 base period, the total cost for ventilation is going to increase significantly, unless other control measures, are used to cut the ventilation requirements.

COST OF OTHER CONTROL MEASURES

Even with the present cost, we should be looking at all of the other available control measures. In recent years there has been an attempt by the Bureau of Mines and others to arrive at cost factors for other control techniques. The U.S. Environmental Protection Agency (EPA) sponsored a 2-month study that resulted in a report by Kown (9). This study considered the mine as a whole and its total production of radon, 8.86 Ci/day. Some of the radon reductions and costs given by Kown (9) are shown in table 12. Other control measures such as mine pressurization, the use of highly reactive chemical oxidants, and specialized mining techniques were discussed, but costs were not calculated.

TABLE 12. - Costs for radon control from Kown (9)

Control measure	Radon reduction, Ci/day	Cost per ton
Sealant coatings.....	1.01	$1.45
Bulkheading..........	2.95	.34
Activated charcoal with bulkheading....	3.01	4.32

Cost figures reported by the Bureau of Mines are usually for single installations. For example, the materials cost of an 8- by 14-foot bulkhead was $186 to $295 (7). Radon barrier sealant costs per square foot have been $0.30 to $1.19 ($0.46 to $1.84 in 1980 dollars) (4). The most expensive coating system was the least satisfactory material because it contained chopped fiberglass. Field tests of sealants showed radon-stopping power of up to 75 percent; therefore, they can reduce the amount of ventilation needed to control the radon-daughter concentrations to a given level.

Cost figures like these can be compared with the cost for ventilation control. To accomplish this, the cost of a control measure must be expressed in the same units as ventilation costs--dollars per ton--and the effect of the new control measure must be defined. For example, cost per square foot is the most convenient for sealant coatings, and this can be related to a cost per ton by considering the surface area remaining in the excavation of typical drifts. In a 6- by 7-foot opening, about 8.2 square feet of rock is exposed around the periphery for each ton of rock removed; for a 12- by 14-foot drift, about 4.1 square feet of surface is left per ton of rock removed. Therefore, sealant coatings cost about $2 or $3 per ton (1980). This is considerably less than the estimated $5.43 per ton for present radon-daughter control.

CONCLUSIONS

The available radiation control cost information has been analyzed and yielded the equation: Cost, 1967$/ton = $3.134\ (WLM)^{-0.3715}$. Combining limiting miner exposure, LME, and consumer price index, CPI, the dollars per ton (DPT) can be estimated from $DPT = 0.03624\ CPI\ (LME)^{-0.3715}$. The 1967 cost per ton for a number of average and limiting miner working-level-month exposures has been calculated and converted to a 1980 CPI value. At a LME of 4 WLM, the projected cost per ton for radiation control is $5.41. If the LME is reduced to 0.7 WLM, the projected cost per ton is $10.34. These values are only applicable to radiation control in U.S. sandstone-type mines. Considering the projected costs per ton, any reasonable technology should be used in the control of radon and radon-daughters.

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